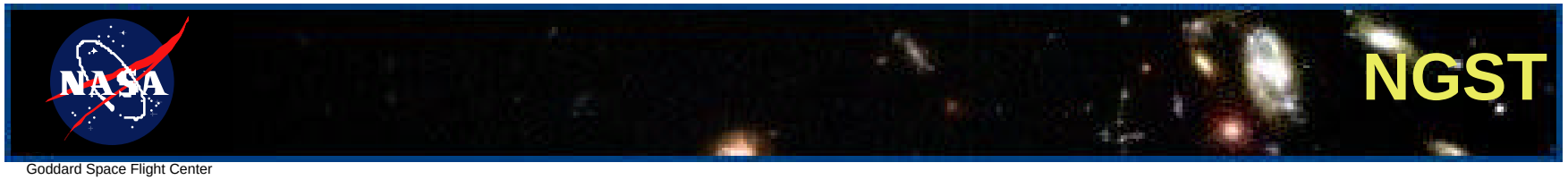

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Thermal Expansion Effects

In

Beryllium Mirrors

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Overview

- Tasked to:
  - Look at thermal expansion effects in beryllium mirrors
  - Generate typical deformed mirror shapes for analyzing mirror figure control using low number of actuators

- Investigated:
  - Beryllium CTE data from MSFC
  - Relationship between radius of curvature change (ΔRoC), change in sagitta, and bulk thermal expansion between mirror segments
  - Analyzed mirror deformations due to CTE non-homogeneity within in a single mirror segment

Beryllium CTE Decreases Significantly At Low Temperatures

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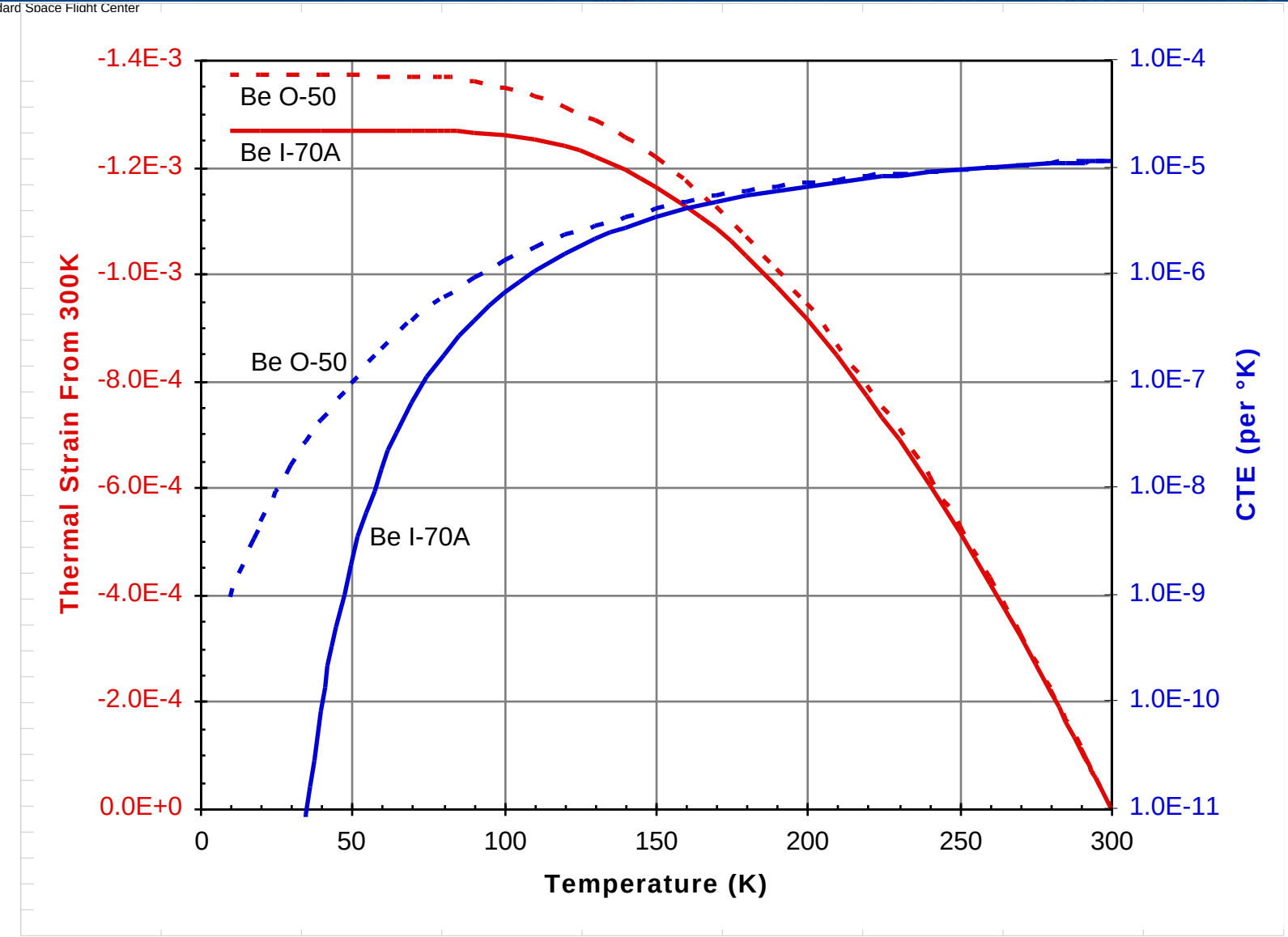

Data from Oak Ridge National Lab via Paul Luz @ MSFC

Allowable Bulk Thermal Expansion

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ΔRoC = Change in radius of curvature

$\Delta RoC = RoC \times \varepsilon_T$

ΔZ = Change in sagitta

$\Delta RoC \quad \Delta Z \times 8 \times (RoC/D)^2$

For RoC = 20 m & D = 2 m, ΔRoC/ΔZ = 800

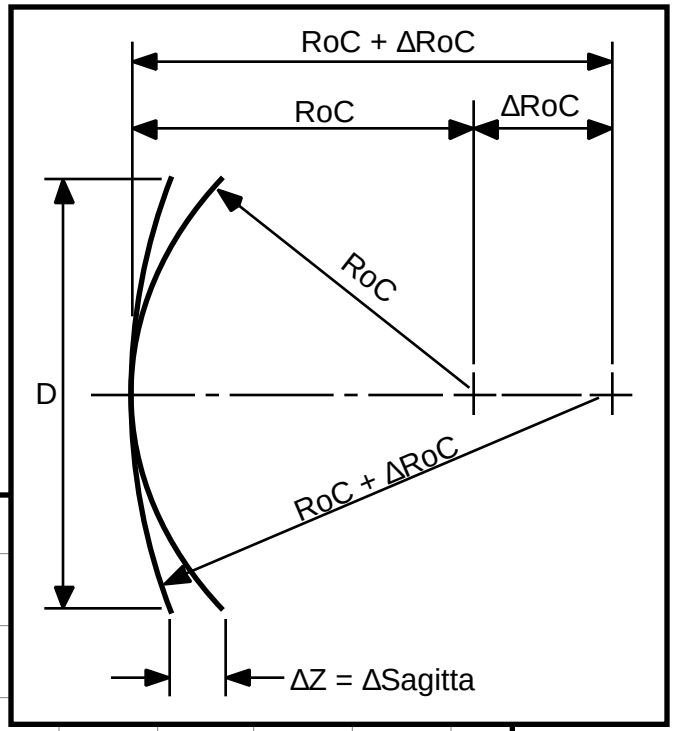
$WFE_{PV} = 2 \times \Delta Z$

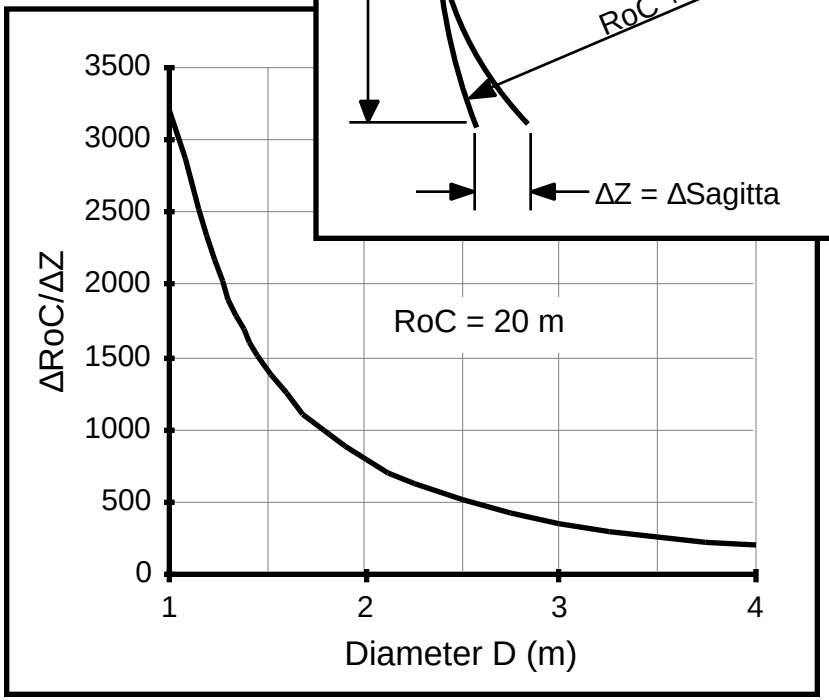
For $WFE_{PV} \leq 0.1$ μm, ΔZ ≤ 0.05 μm

$\Delta RoC = \Delta Z \times \Delta RoC/\Delta Z \leq 40$ μm

$\varepsilon_T = \Delta RoC/RoC \leq 2E\text{-}6$

<u>Maximum allowable bulk thermal strain difference between mirror segments is 2E-6</u>





Matching Segment RoC Requires Cryo-Figuring or Mirror Shape Actuators

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- Scenario: Mirror segments figures measured at T_{FIG} & used at T_{OP}

$$\varepsilon_T = \int_{T_{FIG}}^{T_{OP}} CTE(T)\, dT \approx \text{1E-3 for } T_{FIG} = 295K \text{ \& } T_{OP} = 50K$$

→ 500X larger than maximum thermal strain differential of 2E-6, but acceptable if uniform and repeatable across all mirror segments

- What is impact of variations in parameters?

$$\text{var } \varepsilon_T = \text{var } T_{OP} \times CTE(50K) + \text{var } T_{FIG} \times CTE(295K) + \text{var CTE}$$

var T_{OP}	var T_{FIG}	var CTE
var $T_{OP} \approx \pm 20K$	var $T_{FIG} \approx \pm 1K$	var CTE $\approx \pm 0.1 \sim 1\%$
CTE @ 50K $\approx$ 1E-8 K^{-1}	CTE @ 295K $\approx$ 1E-5 K^{-1}	var $\varepsilon_T \approx \pm$1E-6 ~ 1E-5
var $\varepsilon_T \approx \pm$2E-7	var $\varepsilon_T \approx \pm$1E-5	Probably not acceptable
Acceptable	Not acceptable	

Must cryo-figure or correct figure with actuators

Single Mirror Segment Thermal Deformation Analysis

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- NASTRAN FEM analysis
  - 2 m X 2 m X 4 mm with 20 m RoC
  - 40 X 40 quadrilateral plate elements
- BNQK Mounting (BNQK = Bely Not Quite Kinematic)
  - Constrained at 4 points with XYZ + XZ + Z + Z constraint directions (Z-axis normal to mirror surface
  - Over constrained in Z-direction
  - Extra Z-direction constraint represents an actuator at that point enforcing zero out-of-plane motion
- Thermal load: CTE = 1E-5 K^{-1} & ΔT = 1K
  - Represents thermal load of:

1K ΔT at 295K

or

1% variation in integrated CTE over temperature change of 295 to 50K

Effect of Temperature or CTE Variation Within a Beryllium Mirror Segment

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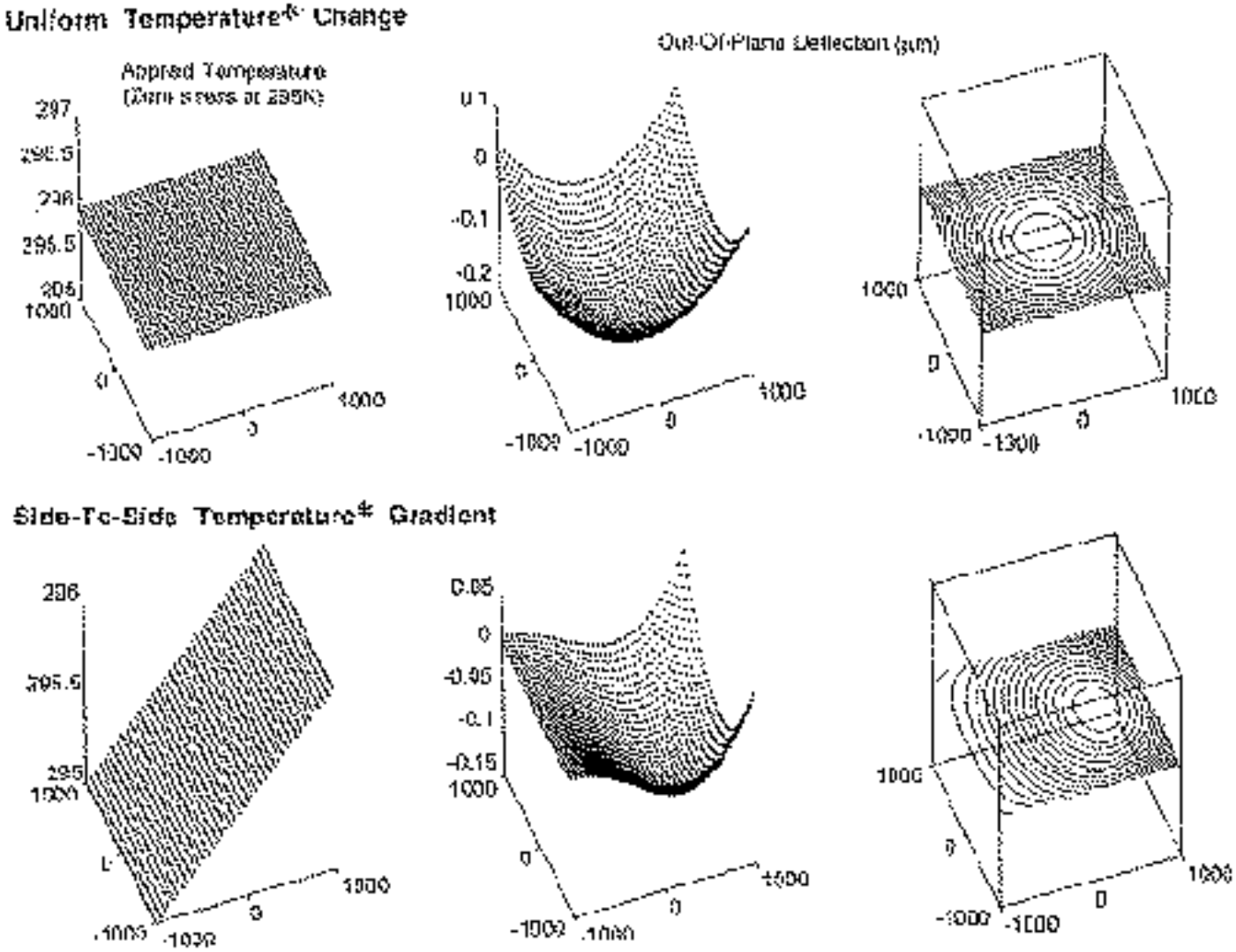

* CTE = 1E-5 K^{-1} → Thermal distortions valid for 1°K ΔT @ 295K or 1% CTE variation combined with 295 to 50K ΔT

Effect of Temperature or CTE Variation Within a Beryllium Mirror Segment

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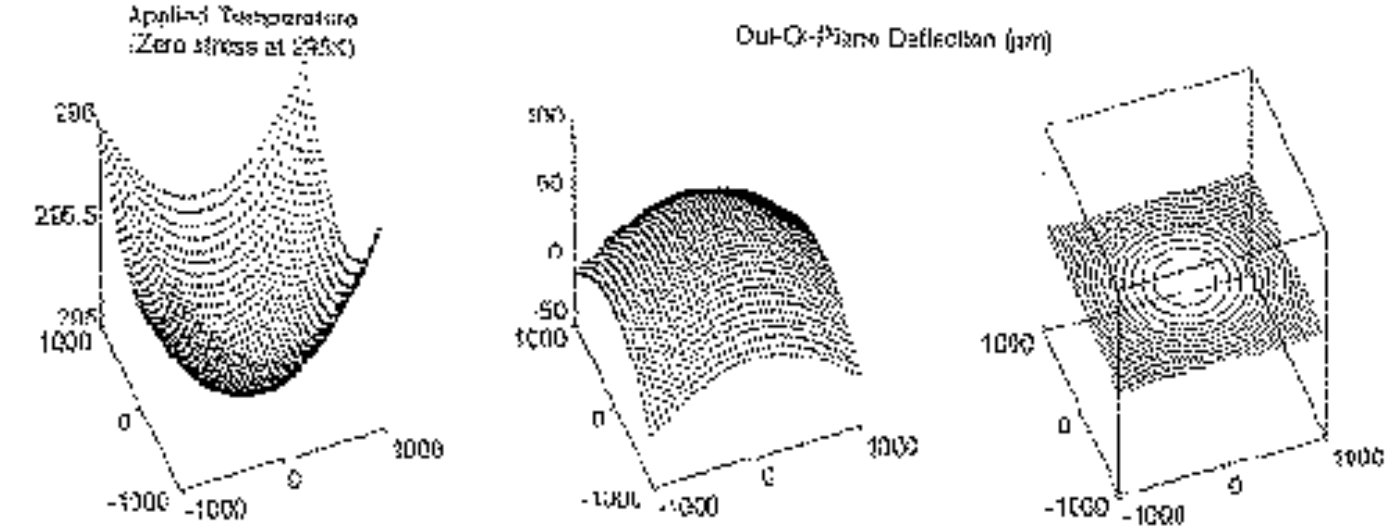
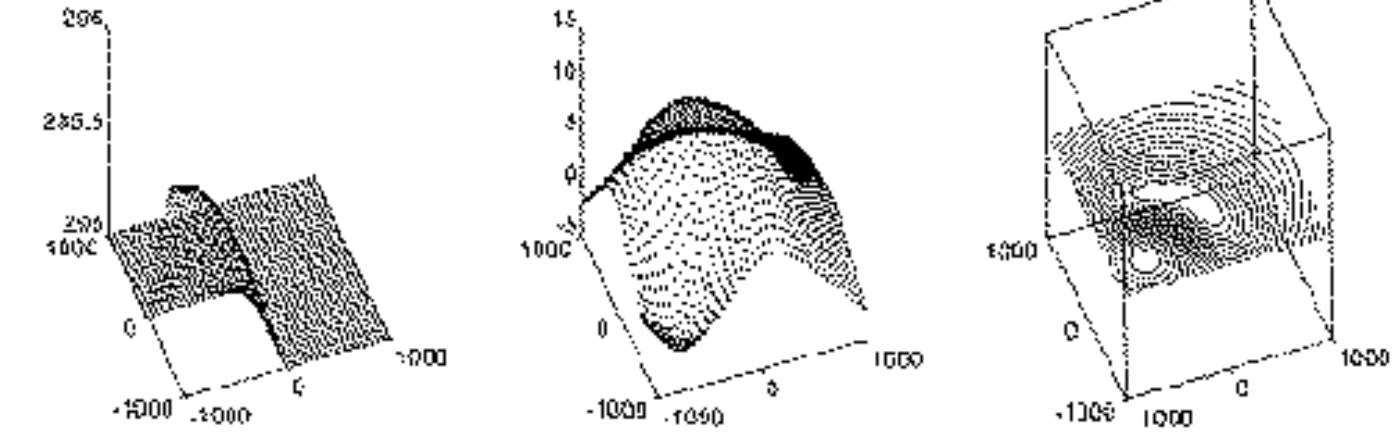
Radial Temperature* Gradient



Local Temperature* Variation



* CTE = 1E-5 K^{-1} → Thermal distortions valid for 1°K ΔT @ 295K or 1% CTE variation combined with 295 to 50K ΔT

Summary

- Bulk temperature change effects
  - Thermal strain difference between mirror segments must be < 2E-5 to keep WFE_{PV} < 0.05 µm due to relative RoC changes
  - Thermal strain difference of <2E-5 very likely not achievable due to segment-to-segment variations in bulk CTE or T_{FIG}
  - Therefore, cryo-figuring or actuator correction required

- Effects due to variation of CTE within a mirror segment
  - Mirror surface errors highly dependent on how CTE varies spatially
  - Believe hoop stress is reason for greatly increased thermal deformations in some cases
  - Mirror with higher ratio of bending stiffness to in-plane stiffness (isogrid or sandwich plate design) should be less sensitive to CTE variations
  - Additional study required to understand range of deformations possible and if deformations are correctable with sparse actuator array